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# Topology optimization of nano-photonic systems

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**Abstract:** We describe recent developments within nano-photonic systems design based on topology optimization. Applications include linear and non-linear optical waveguides, slow-light waveguides, as well as all-dielectric cloaks that minimize scattering or back-scattering from hard obstacles.

Topology optimization is a way to distribute material in a design domain in order to optimize a given goal function subject to functional or geometrical constraints. The method is based on repeated system analyses (by e.g. Finite Element/Difference approaches in frequency or time domain) followed by deterministic, gradient-based design updates. Originating in mechanical engineering the method has since then been extended to photonic crystal design problems (Ref. 1, 2, 3). An extensive review of the procedure and its applications in nano-photonics has appeared recently (ref. 4). In the present paper we discuss our recent work (developed after ref. 4) within the field. This encompasses improved modeling capabilities for linear and non-linear time domain problems, robustness with respect to manufacturing errors and the systematic design of all-dielectric cloaking devices.

### A parallel FDTD code for topology optimization

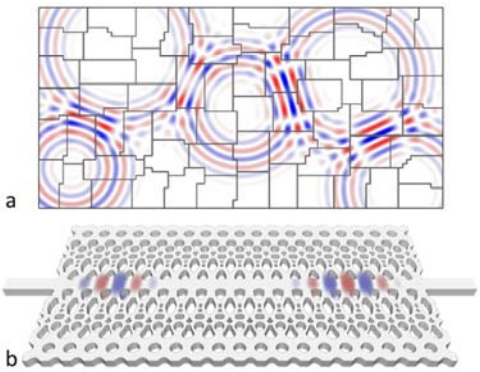


**Figure 1 a)** Mesh partitioning for distribution of processes on parallel computer. **b)** Snap-shot of simulations results for 40M cell PhC slowlight waveguide test problem.

Topology optimization requires repeated function evaluations and hence especially for 3d problems computational efficiency is imperative. For this purpose we have developed an in-house FDTD code that is fully parallelized and which scales linearly on up to 144 CPUs. With the code we can solve 2D problems with 50k time steps on a 1000x500 grid in less than 15 seconds and 3d problems with 50k time steps on a $1000\times500\times80$ grid (40M cells) within 40 minutes. Presently, the code is being extended with gradient analysis and topology optimization capabilities and first topology optimization results will be presented at the congress. Mesh partitioning and snap-shot from the modelling of a slow-light photonic crystal-based waveguide is shown in Fig. 1.

### Robustness towards manufacturing errors

Waveguides, resonators and other nano-photonic structures are extremely sensitive to manufacturing uncertainties such as under- or over-etching. We have included such uncertainties in the design process (ref. 5). This is achieved by optimizing for the worst case of the original, under- or over-etched structure or by optimizing for the mean performance value with a constraint on the variance.

### Topology optimization of non-linear switches

We have recently extended the topology optimization method to include non-linear nano-photonic problems (ref. 6). Specifically we design a 1D photonic switch where one material is passive (air) and one is Kerr-nonlinear. Compared to a simple Bragg-grating-based switch operating at the band edge we achieve a significant improvement of the switch performance in both open and closed states as demonstrated in Fig. 2. Simultaneously, improved robustness towards manufacturing variation is ensured as described in the previous subsection.

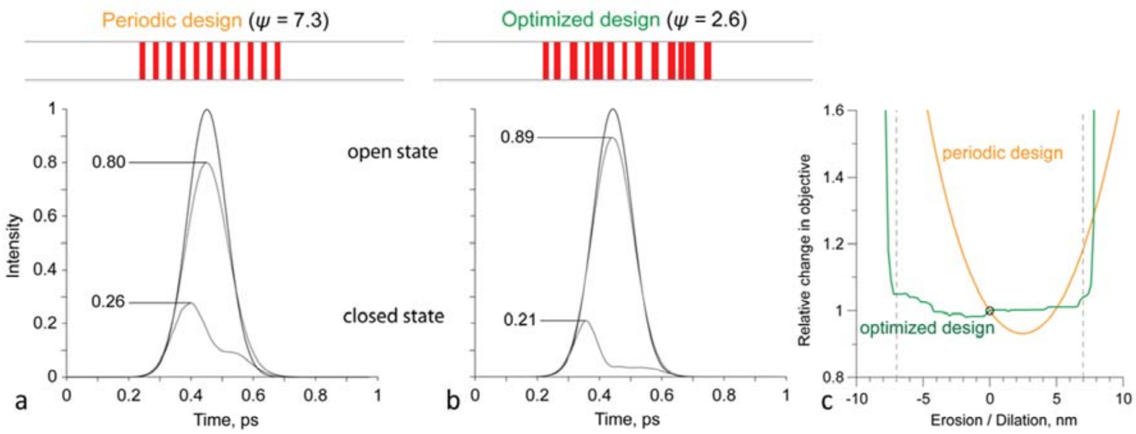


**Figure 2 a)** Performance in open and closed states for simple Bragg-based non-linear photonic switch. **b)** Performance of optimized switch. **c)** Due to the robust optimization approach the optimized switch is less sensitive to under- or over-etching.

## Topology optimization of all-dielectric cloaks

The art of cloaking, i.e. making objects invisible to the observer by wrapping them in appropriately designed optical cloaks, has received a lot of attention. So-called carpet cloaks can be realized with simply perforated dielectric materials whereas real cloaks (e.g. hiding cylinders) are difficult to realize due to the requirement of extreme electromagnetic material properties. In a number of studies we have used topology optimization to come up with simple dielectric cloaks that perform almost perfectly but only for a limited number of angles (ref. 7). Fig. 3 shows a dielectric cloak design optimized for 2 incoming wave angles. Apart from this full-cloaking example we will show surprisingly simple results obtained for the reduced problem of only considering minimization of back-scattering.

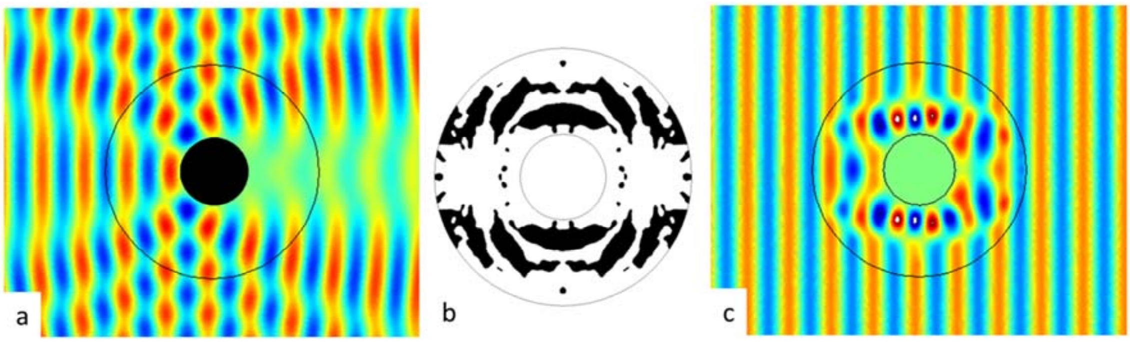


**Figure 3** Design of all-dielectric cloak using topology optimization. **a)** Scattering from hard cylinder. **b)** Topology optimization dielectric material distribution in cloaking domain (white: air, black: dielectric material, $\varepsilon_r$=2). **c)** Scattering from cloaked cylinder.

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